Polymeric multimode waveguide based electro-optic modulator with a vertically configured dumping planar waveguide

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An electro-optic modulator based on a polymeric multimode waveguide coupler was developed. A guiding multimode waveguide with a vertically configured dumping planar waveguide was employed in the design to increase the device packing density. A modulation depth of 91% at 1330 nm was experimentally achieved. This device shows that the multimode optical waveguide with the vertically configured dumping planar waveguide is promising in electro-optic modulator designs. This modulator can be used in multimode optical interconnection systems such as data communications and fiber sensor networks. © *2002 American Institute of Physics.*
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The rapidly increasing demand of communication bandwidth drives the research and development in several areas of optical communication, such as advanced information processing, optoelectronic interconnections, and fiber-optic communications.[1,2] Due to the ability of high-speed modulation and low signal distortion, external electro-optic (EO) modulators are important devices in fiber-optic communications.[3–5] Many research efforts have been put in single-mode waveguide based EO modulators for long-haul telecommunications where single-mode optical fibers are typically deployed. For short distance interconnection applications, however, multimode optical interconnection systems can satisfy the distance and bandwidth requirements.[6–9] The employment of multimode optical fibers in a short distance optical interconnection system provides much lower insertion loss than that of single-mode optical fibers.[1,6–8] To interconnect with multimode optical fibers, multimode waveguide based modulators are needed for easy alignment and high packaging reliability.[10,11] We have developed a multimode waveguide based EO modulator[12] for multimode optical fiber interconnection. In this letter, we present a design that configures the guiding waveguide and the dumping planar waveguide vertically. This device has a higher packing density than the coplanar configured EO modulator.[12] A modulation depth of 91% was experimentally achieved at 1330 nm. This device shows that the multimode optical waveguide with the vertically configured dumping planar waveguide is promising in EO modulator designs.

The schematic structure and the cross section of the real device are shown in Figs. 1 and 2, respectively. The device consists of a multimode rib waveguide designed for signal guiding, a pair of modulating electrodes, and a planar dumping waveguide under the guiding multimode waveguide. The guiding multimode waveguide and the dumping planar waveguide were separated by a low-index polymer buffer layer. The dumping planar waveguide was designed to be highly lossy (~ 26 dB/cm) so that the optical energy coupled from the guiding multimode waveguide can be efficiently dumped out. The width of the rib waveguide is 50 μm and the thickness of the waveguide is 5.1 μm. The guiding multimode waveguide can support 136 modes. Using the BEAM-PROP simulation software from R-Soft Inc., we simulated the coupling from the multimode guiding waveguide to a standard 50 μm multimode optical fiber. The coupling loss can be less than 0.1 dB, which indicates a good match between the modes of the multimode waveguide and those of the multimode optical fiber.

Following Ref. 10, the mode coupling equation can be expressed as

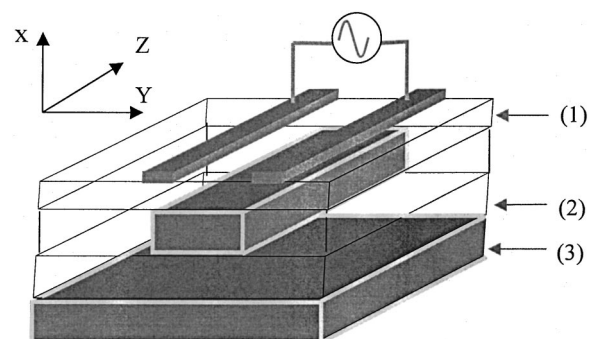$$\frac{dA_{jm}}{dz} = i\beta_{jm}A_{jm} + k_{jm,j'm'}B_{j'm'}, \tag{1}$$

FIG. 1. Structure of the unidirectional electro-optical modulator. (1) top cladding, (2) buffer layer, and (3) dumping planar waveguide. The solid rectangle channel is the guiding multimode waveguide. The top modulating electrodes and the guiding multimode waveguide are separated by the top cladding layer. Note that the guiding multimode waveguide and dumping planar waveguide are vertically configured.
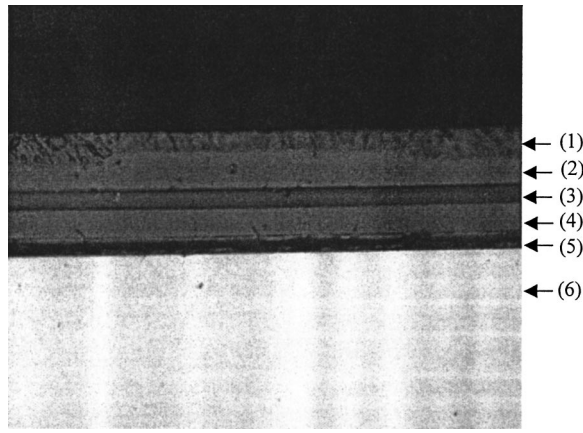
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FIG. 2. Cross section of the real device structure. (1) UV15 top cladding, (2) guiding rib waveguide, width: 50 μm, step height: 1.6 μm, (3) 2.7 μm NOA61 buffer layer, (4) 5.1 μm planar dumping planar waveguide, (5) 2.2 μm U9020 bottom cladding layer, and (6) silicon substrate.

$$\frac{dB_{j'm'}}{dz} = i\beta_{j'm'}B_{j'm'} + k_{j'm',jm}A_{jm} - \alpha_{j'm'}B_{j'm'}, \quad (2)$$

where A_{jm} is the amplitude of the (j,m) mode in the guiding multimode waveguide, $B_{j'm'}$ is the the amplitude of the (j',m') mode in the dumping planar waveguide, β_{jm} is the propagation constant of the (j,m) mode, and $k_{jm,j'm'}$ is the coupling constant between the modes of guiding multimode waveguide and dumping planar waveguide.

The coupling efficiency from the mode (j,m) of the guiding multimode waveguide to the mode $(j'm')$ of the dumping planar waveguide can be expressed as

$$D_{jm,j'm'} = \frac{k_{j'm',jm}^2}{\psi_{jm,j'm'}^2}(1 - e^{-\alpha_{j'm'}L}) \cdot \sin^2(\psi_{jm,j'm'}L), \quad (3)$$

$$\psi_{jm,j'm'} = (k_{jm,j'm'} \cdot k_{j'm',jm} + \Delta_{jm,j'm'}^2)^{1/2}, \quad (4)$$

$$\Delta_{jm,j'm'} = k|N_{jm} - N_{j'm'}|/2, \quad (5)$$

where N_{jm} and $N_{j'm'}$ are the effective indices of the (j,m)th mode and the (j',m')th mode, respectively, $\alpha_{j'm'}$ is the loss coefficient of the mode $(j'm')$. The reverse coupling efficiency from the mode $(j'm')$ of the dumping planar waveguide to the mode (j,m) of the guiding multimode waveguide can be expressed as

$$\eta_{j'm',jm}^\alpha = \frac{k_{j'm',jm}^2}{\psi_{jm,j'm'}^2} e^{-\alpha_{j'm'}L} \cdot \sin^2(\psi_{jm,j'm'}L). \quad (6)$$

Note that if $\alpha_{j'm'}$ is high enough, the reverse coupling efficiency from the mode $(j'm'.)$ of the dumping planar waveguide to the mode (j,m) of the guiding multimode waveguide is very negligible so that the unidirectional coupling is achieved.[10]

The electrodes were designed to electro-optically control the phase matching condition of the coupling between the guiding multimode waveguide and the dumping planar waveguide. Because there is only one guiding multimode waveguide in this structure, the device packing density (number of modulators per unit area) is higher than that of
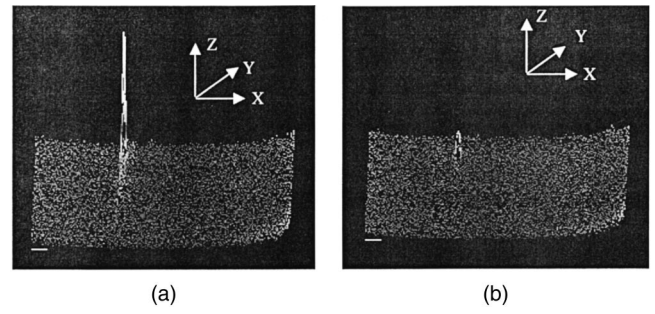

FIG. 3. Three-dimensional intensity profile of the EO modulator output at 1330 nm. Z axis is the output intensity in arbitrary unit, X, Y plane is the screen the output light was focused onto. (a) With the applied modulating voltage of 0 V. (b) With the applied modulating voltage of 50 V.

devices with a coplanar configuration,[12] where the guiding multimode waveguide and the dumping planar waveguide are configured in the same layer.

The fabrication of the device followed the conventional lithography technique used in very large scale integrated fabrication. A 130 Å chromium and a 2000 Å gold layer were first deposited on a silicon wafer as the bottom poling electrode, the chromium layer was used to improve the adhesion between gold layer and the silicon substrate. A 2.2 μm U9020 was then spincoated as the bottom cladding. The refractive index of U9020 was measured 1.51 at 1330 nm under transverse magnetic (TM) polarization. A 5.1 μm poly (methyl methacrylate) (PMMA)/DR1 was then spincoated as the dumping planar waveguide. The refractive index of PMMA/DR1 was measured 1.57 at 1330 nm under TM polarization. Then, a 2.7 μm polymer NOA61 was spin-coated as the buffer, which has a refractive index of 1.54 at 1330 nm under TM polarization. A 5.1 μm PMMA/DR1 was then spincoated as the guiding multimode waveguide layer. A 2000 Å gold was then deposited on top the guiding multimode waveguide layer to function as the top contact poling electrode. The sample was then poled at 113 °C, the glass transition temperature of PMMA/DR1, under 800 V dc voltage using contact poling method. The nonlinear coefficient γ_{33} was measured 12 pm/V. After contact poling, the top poling electrode was removed by wet etching. The guiding multimode waveguide was then formed by reactive ion etching. A 2.6 μm Master Bond UV15® was then spincoated as the top cladding. The refractive index of UV15 was measured 1.49 under a TM polarized laser beam at the wavelength of 1330 nm. A pair of top modulating electrodes were then formed by metal deposition followed by photolithography and wet etching procedure.

To test the device, a 1330 nm TM polarized laser beam was endfire coupled into the device through a 40× objective lens. The output light was collimated by another 40× objective lens and then imaged onto a screen. An IR camera was used to obtain the near field real-time image, which was then collected by a computer and analyzed by the SPIRICON™ beam analyzer. Figures 3(a) and 3(b) show the intensity profile of the output beam from the guiding multimode waveguide at the applied voltages of 0 and 50 V, respectively. Note that when the applied modulating voltage was 50 V, the output signal intensity was decreased providing the phase matching condition was satisfied. To measure the dynamic modulation of the device, a 10 kHz triangle electrical signal
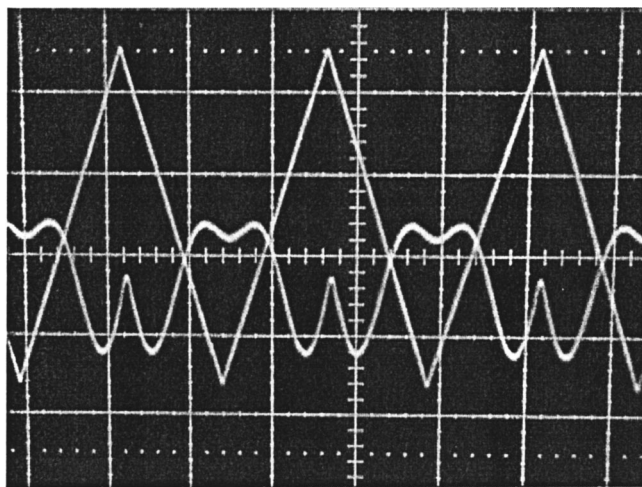
FIG. 4. Dynamic response of the electro-optical modulator at 1330 nm. Upper trace: 10 kHz modulating signal, lower trace: response of the EO modulator.

was applied to the modulating electrodes. The output signals from the guiding multimode waveguide were detected by a $p-i-n$ photodetector. Figure 4 shows the dynamic response of the device. The upper trace was the triangle modulating signal and the lower trace was the response of the device. The modulating depth was measured 91%.

In summary, we report on a polymeric multimode waveguide based electro-optic modulator. Due to the vertical configuration of the dumping planar waveguide, the device has a higher device packing density than that of coplanar configured multimode EO modulator. An EO modulation depth of 91% has been experimentally observed. This device can be used to interconnect the multimode optical fibers in multimode communication systems such as data communications and fiber sensor networks.

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